APPENDIX B

INTERIOR AREA ANALYSIS EXAMPLES

This Appendix presents example procedures for performing interior area coincident flood frequency analyses at outlets through the line-of-protection. The examples are for: (1) period-of-record; (2) multiple discrete events; and (3) coincident frequency analyses procedures, Exhibits 1, 2, and 3, respectively. The examples emphasize the coincident analysis concepts for planning feasibility studies. Hydrologic and hydraulic aspects of interior areas are described only in the detail necessary to understand the overall analysis strategy. The reader should not apply these procedures without complete understanding of the needs and peculiarities of the study area under investigation. Study strategies presented herein would likely require some modifications for application to other study areas.

EXHIBIT B1

PERIOD-OF-RECORD ANALYSIS EXAMPLE

B1-1. Purpose.

This exhibit describes with a case example the period-of-record analysis procedure for performing hydrologic studies of a leveed interior area. The example emphasizes concepts in a feasibility study setting. The reader should be familiar with the material in paragraph 4-5 prior to studying this example.

B1-2. General Study Background.

a. The Corps of Engineers is performing a feasibility study of remedies for interior flooding of the Nelson Drainage and Levee District, an agricultural area in the Smith River Valley. The area is protected from direct river flooding to a two-percent chance exceedance frequency event by a main levee and a tie back levee (See Figure B1.1). The interior area consists of 5,000 acres in the Smith River flood plain and receives runoff from about 300 acres of adjacent hill land. Runoff is conveyed through the interior area by a network of lateral ditches and main channels. The only outlet for interior runoff is an existing gravity outlet comprised of double 60 inch diameter culverts through the line-of-protection. During large events water from the Olson Pond Drainage and Levee District overflows into the study area.

b. Agricultural crop flood damage has resulted from ponding of local runoff adjacent to the line-of-protection. Damage occurs during prolonged periods of blocked gravity outflow caused by high river stages. Flooding commonly occurs in the spring months. Approximately one-half of the area has been inundated three times during the past 10 years.

B1-3. Study Strategy.

a. Reconnaisance level studies found that significant flood damage potential existed in the interior areas and that it is justified to study alternative flood loss reduction plans. These plans include combinations of modifications to ditches, channels, and gravity outlets, and the installation of pumping facilities. Period-of-record analysis procedures are used to develop hydrologic data for agricultural flood damage assessments, optimal sizing of additional gravity outlets and pumping facility capacities, and selection of pump operating criteria. Data requirements and hydrologic analysis procedures used in the plan formulation portion of the study are described in paragraph 4-5 Period-of-Record Methods and shown schematically on Figure 4.2.

b. Period-of-record analysis procedures are applicable because of the availability of long-term precipitation and exterior stage data, the agricultural nature of flood damage, and the simplistic nature of the interior drainage pattern at the major damage center. Flood damage evaluations may be computed directly from each historic event by accounting for season, magnitude, and duration of the event. Annual pump operation times may also be directly calculated.

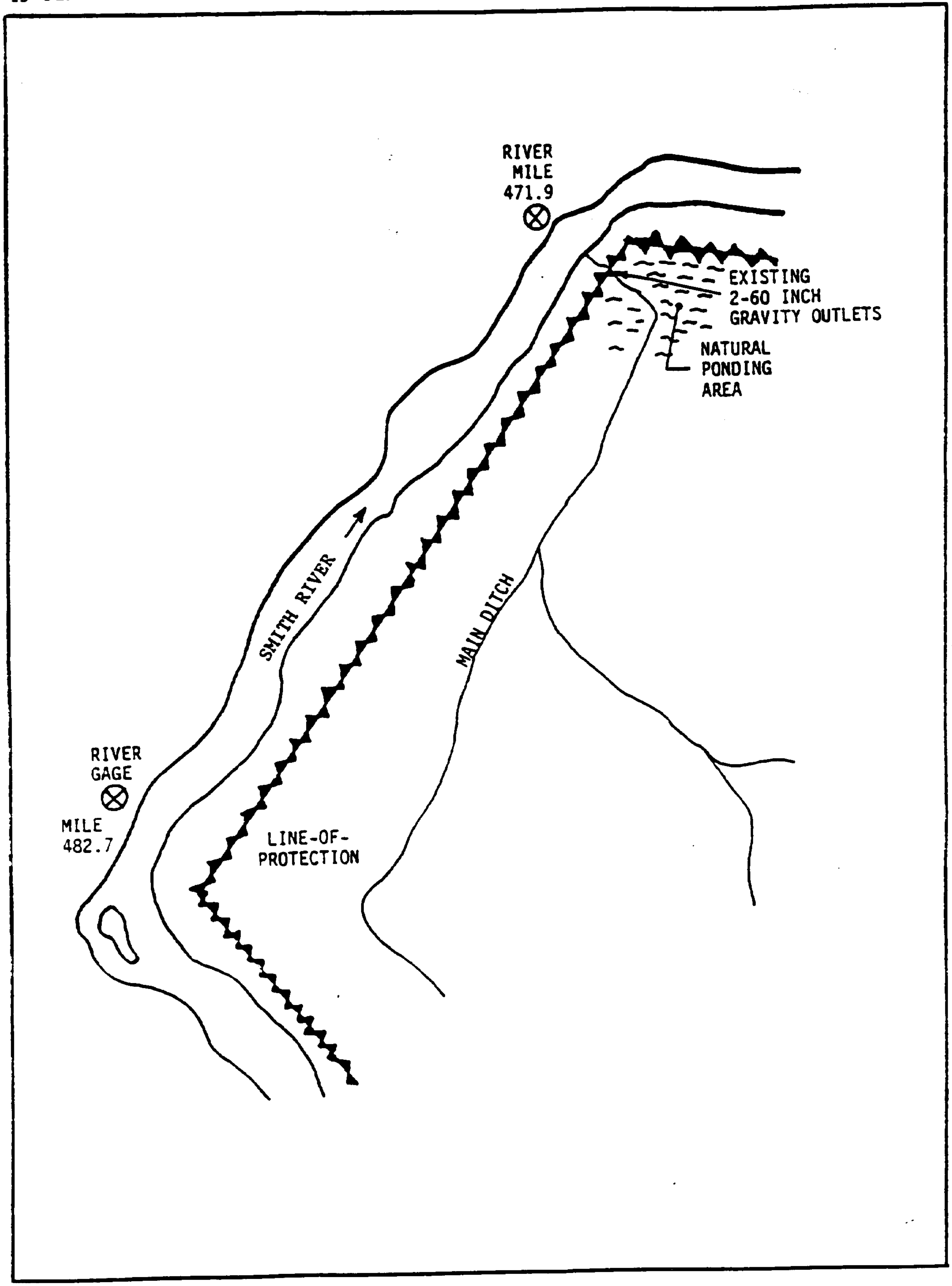


FIGURE B1.1 Study Area Map

c. The period-of-record analysis is performed for with and without proposed improvement for existing and future conditions. The existing condition minimum facility (reference paragraph 3-2) is assumed as the gravity outlet presently in place. The formulation strategy involves initial evaluations of additional gravity outlet capacity (ultimately found not feasible) and subsequent analysis of various pumping facility sizes. A period-of-record assessment is performed for the existing conditions without a proposed improvement project, and for each gravity outlet and pumping facility size. Since no change in the agricultural area is projected throughout the project life, future hydrologic conditions are the same as existing conditions.

B1-4. Hydrologic Analysis Methods.

a. General. Analysis of the interior area is based on data requirements for period-of-record precipitation-runoff response parameters, ponding area geometry, seepage, overflow runoff into the study area, gravity outlet and pumping capabities, and exterior stage conditions. Calculations involving these parameters are performed at 24-hour intervals for the 50-year period-of-record selected for analysis. Interior hydrographs are subsequently generated and routed through the line-of-protection. The resulting interior stage-hydrographs are used in damage calculations. The formulation strategy analyzed several sizes of gravity outlets and pumping station capacity.

b. Historic River Stage Data. Historic river stage data are required at the gravity outlet and proposed pumping facility location (river mile 471.9) to perform the period-of-record coincident routings through the line-of-protection. The period-of-record stage data are developed from the historic record of the nearby streamgage (river mile 482.7) using a river transfer relationship (Table B1.1). The transfer relationship is derived by determination of differences in elevations of similar water surface profiles between the two locations

Table B1.1
River Elevation Adjustment
Relationship

Elevation at River Gage Mile 482.7	Elevation at Interior Pond Gravity Outlet River Mile 471.9
368.0	361.2
370.0	363.1
372.0	365.1
374.0	367.0
376.0	369.0
378.0	370.9
380.0	372.7
390.0	382.2
400.0	391.8

c. Precipitation Data. A daily time interval was selected as appropriate for this period-of-record analysis. Review of exterior stage and daily precipitation records obtained on magnetic tape from the U.S. Geological Service and National Weather Service, respectively, indicate an analysis period of up to 50-years may be used. This period-of-record length is considered adequate for the agricultural study area. Daily rainfall values were obtained from National Weather Service data at three nearby raingages and used to develop a rainfall distribution pattern for the study area. This is accomplished by weighting the respective contribution of each raingage based on the distance of the gage from the center of the study area.

d. Rainfall-Runoff Analysis. The daily time interval and interest in volume (instead of peak flow) of inflow into the interior ponding area enables the adoption of a simplified rainfall-runoff analysis procedure. The generated daily precipitation data for the study area is adjusted by seasonal loss factors to obtain rainfall excess (Table B1.2). The excess values are multiplied by the drainage area to obtain the volume of inflow into the interior ponding area. Channel routing is not required due to the small basin and daily time interval of analysis.

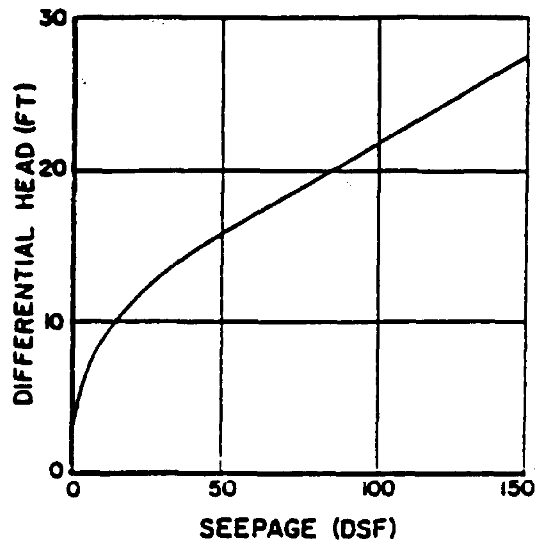
Table B1.2
Seasonal Runoff Factors
for Rainfall Excess Calculations

Season	Factor
Winter (Dec - Feb)	.55
Spring (Mar - May)	.73
Summer (Jun - Aug)	.65
Fall (Oct - Nov)	.70

e. Seepage. A secondary inflow into the ponding area is seepage which occurs through or under the line-of-protection during high exterior river stages. A relationship of seepage rate versus the differential head between the interior pond and exterior river stage is estimated based on pumping tests of interior relief wells installed for levee stability and estimates by foundation engineers obtained from similar studies. The total seepage includes inflow adjacent to the levee, beyond the levee, and from relief wells. A one day lag time is used to simulate estimated transmission rates. Figure B1.2 shows the seepage rate versus head relationship.

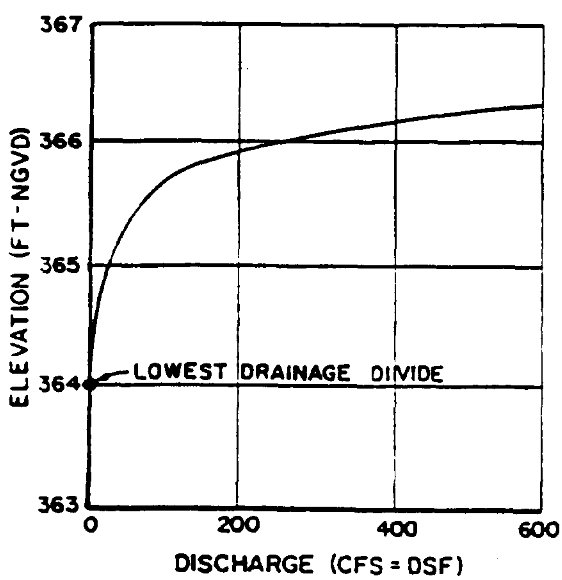
f. Overflow. The rating curve developed to characterize the overflow of water from the study area into adjacent areas is shown on Figure B1.3. The relationship is based on a normal depth rating curve for the cross-section overflow areas.

g. Interior System Characteristics. The physical characteristics of the interior system defined for the analysis are the ponding area, conveyance ditch systems, gravity outlets, and pumping stations. Their locations are shown on Figure B1.1.



Day-second-feet (DSF) = 1 cubic-foot per second for 24 hours

FIGURE B1.2 Head vs. Interior Seepage Relationship



Day-second-feet (DSF) = 1 cubic-foot per second for 24 hours

FIGURE B1.3 Interior Ponding Area Overflow Relationship

(1) Ponding Area. The interior ponding area is adjacent to the line-of-protection at the gravity outlet and proposed pumping facility location. The main ditch flows into the ponding area. The area is defined for analysis by an elevation-storage relationship shown in Figure C1.3. The major damage to crops in the interior area occurs from ponding in this area.

(2) Conveyance. The small lateral interior ditches flow into the main channel of the interior system which conveys flood waters to the ponding area. Inflow to the ponding area is governed by the conveyance capacity of the channel. Figure B1.4 shows the channel inflow rating curve (elevation-discharge relationship). The inflow is dependent on the elevation of the ponding area.

(3) Gravity Outlets. The double 60 inch gravity outlet conveys water from the ponding area through the line-of-protection. The outlets function only for a positive head conditions (interior pond elevations are higher than the exterior river elevation). The gravity outlet rating functions are plotted for a range of possible flow conditions associated with ponding area and river elevations. Figure B1.5 shows the rating function for the double 60 inch gravity outlet in the study area.

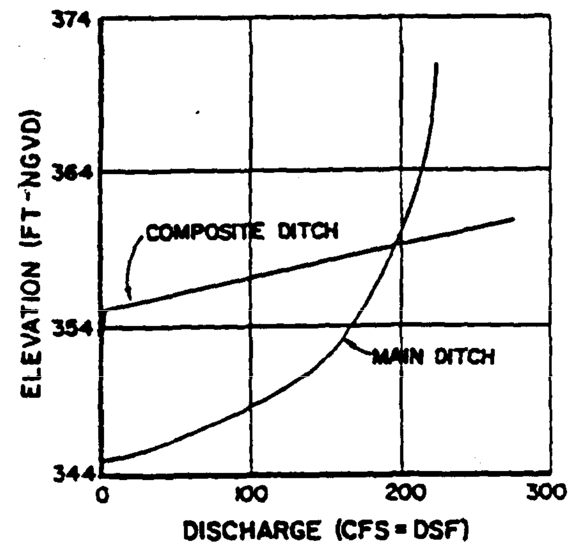
(4) Pumping Facilities. Alternative pumping facility capacities are analyzed as part of the feasibility study. The pump location is adjacent to the ponding area. The pump head-capacity relationship is based on information supplied by pump manufacturers (Table B1.3). Pump start and stop elevations are based on the proposed plan of operation.

Table B1.3
Pumping Facility Criteria
(75 cfs Pump)

Head (Feet)	Efficiency (Percent)
0	100
10	100
15	97
20	93
25	88
30	80
35	50

Start Pump Elevation 348.0
Stop Pump Elevation 346.5

h. Interior Ponding Routing. The result of the period-of-record analysis is a continuous stage hydrograph of the ponding area adjacent to the gravity outlets and proposed pumping facility. The routing is performed by balancing the inflow, outflow, and ponding level for each day of the period of record. Inflow may occur from rainfall runoff, seepage, and overflow from the Olson



Day-second-feet (DSF) = 1 cubic-foot per second for 24 hours

FIGURE B1.4 Interior Area Ditch Rating Curve

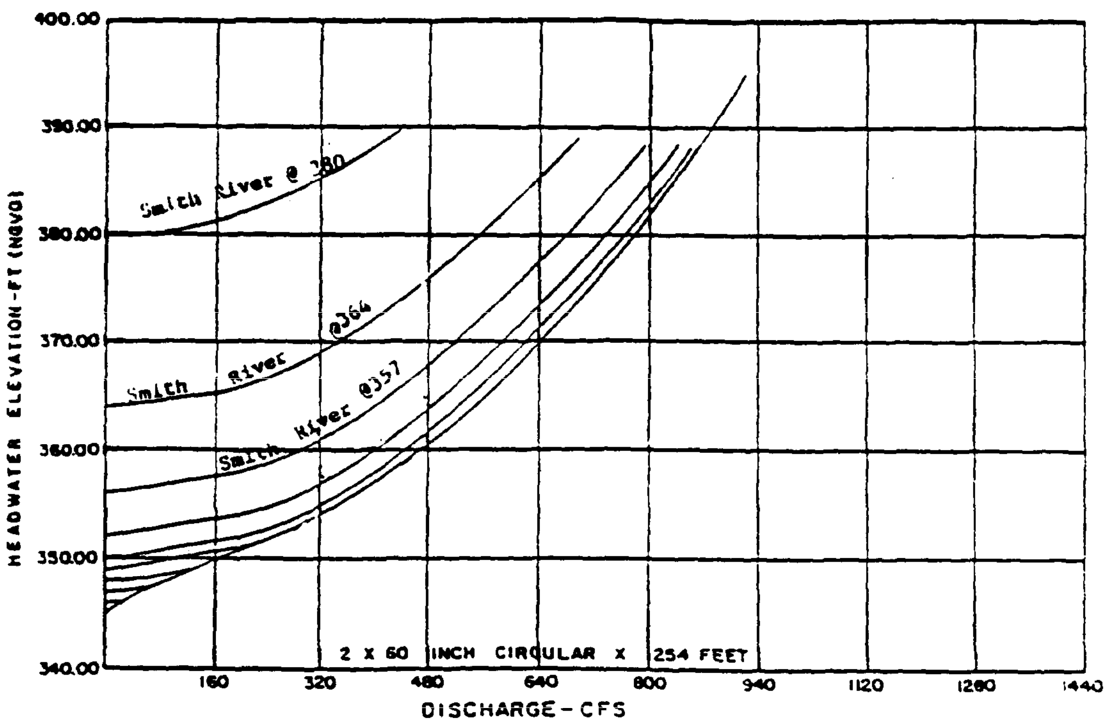


FIGURE B1.5 Gravity Outlet Rating Curve

Ponding Drainage and Levee Districts. Outflow may result from gravity outlets, when the exterior river elevations are lower than the interior ponding stage, and from pumping. The volume of inflow that exceeds outflow is stored in the ponding area.

The period-of-record interior ponding stage may be estimated using the following procedure:

(1) Calculate runoff, seepage, and overflow inflow into the ponding area and add the total volume to the present storage to determine highest possible ponding level;

(2) Calculate the maximum outflow (based on physical constraints) to determine the lowest possible pond level for the period;

(3) Assume a ponding level within the range possible;

(4) Calculate outflow based on interior and exterior stage conditons and associated gravity outflow and pumping capacities;

(5) Reiterate steps (3) to (4) for successive ponding level approximation until the end-of-period storage from two successive iterations varies by less than a specified tolerance;

(6) Continue steps (1) through (5) for the next time interval until the entire period-of-record is analyzed; and

(7) Repeat steps (1) through (6) for other alternatives.

The interior analysis procedure may be performed using a computer program to simulate interior inflows, interior stage conditions, and hydrograph routings through the line-of-protection. Table B1.4 shows an example computation sequence for the 8-17 May 1973 portion of the 50-year period-of-record. The procedure is repeated for each time interval for the entire record. The computer simulation model enables several alternatives of gravity outlets and pumping facility sizes to be analyzed in a single computer run.

i. Calibration Procedure. The period-of-record hydrologic simulation model is calibrated to historic high water marks and the observed frequency of flooding at roads, bridges, structures, landmarks located in the ponding area. Adjustments are made to the initial runoff loss rate parameters and lag time to calibrate the results (peak stages and runoff volumes) to the observed data.

B1-5. Summary.

a. The period-of-record method of analyzing the coincident interior flooding of leveed or walled areas simulates the physical process of inflow, outflow, and ponding area storage and outflow over time. The procedure is especially applicable to analysis of interior systems where the primary concern is at a ponding area adjacent to the line-of-protection.

Table B1.4

Period-of-Record Daily Analysis Example
(8-17 May 1973 Portion of 50-Year Record)

			Ponding Area Area-Capacity Data			Inflow Into Ponding Area			Outflow From Ponding Area		
Date	Rainfall Excess (Inches)	River Elevation (NVGD)	Elev (NVGD)	Area (Acres)	Storage (DSF)	Runoff (DSF)	Seepage (DSF)	Overflow (DSF)	Gravity (DSF)	Pump (DSF)	Overflow (DSF)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
8 May 1973	.01	370.8	358.9	675	746	2	25	0	0	72	0
9 May 1973	.32	371.5	359.0	715	785	85	25	0	0	71	0
10 May 1973	.82	371.5	359.3	889	958	216	28	0	0	71	0
11 May 1973	.01	371.8	359.2	846	916	2	27	0	0	71	0
12 May 1973	0	372.0	359.2	804	874	0	29	0	0	71	0
13 May 1973	0	372.0	359.1	762	832	0	30	0	0	71	0
14 May 1973	0	371.8	359.0	721	791	0	30	0	0	71	0
15 May 1973	0	371.5	358.9	679	749	0	30	0	0	71	0
16 May 1973	0	371.3	358.9	636	707	0	29	0	0	71	0
17 May 1973	0	370.5	358.8	554	663	0	28	0	0	71	0

(1) Calculation time interval (24 hours shown as a date) of the period-of-record used for analysis;
(2) Rainfall excess over study area determined by subtracting losses from the rainfall value associated with each time interval;
(3) River elevation at the gravity outlet;
(4) Interior ponding elevation for time period determined by balancing inflow, outflow and storage of the ponding area;
(5) Area flooded associated with interior ponding elevation;
(6) Storage associated with interior ponding elevation;
(7) Volume of interior inflow to ponding area resulting from rainfall excess;
(8) Volume of seepage inflow to ponding area;
(9) Volume of overflow from adjacent areas into study area;
(10) Volume of gravity outflow from ponding area;
(11) Volume of flood water evacuated from interior ponding area by pumping; and
(12) Volume of flood water which overflows from study ponding area into adjacent area.

NOTE: Day-Second-Feet (DSF) = 1 cubic feet per second (cfs) for 24 hours.

b. The example described here is typical of a single pond analysis for an agricultural area adjacent to the line-of-protection. Exterior stages are determined by transfer of a historic record from a nearby streamgage. The runoff analysis is greatly simplified and uses a daily time interval but is sufficiently accurate for the volume accounting required for this area. Other inflow simulated are overflow from adjacent interior areas (evaluated separately) and seepage. Criteria for operating gravity and pumping outflow are dependent on the differential interior and exterior stages.

c. The flood loss reduction measure formulation process requires analysis of various sizes of gravity outlets and pumping facilities. Alternative gravity outlet invert elevations and pump on-off operation conditions are also evaluated. These assessments require additional analyses of the alternatives for the period-of-record.

EXHIBIT B2

MULTIPLE DISCRETE EVENTS

B2-1. Purpose.

This exhibit describes a case example of the multiple discrete event analysis procedure for performing hydrologic studies of a leveed interior area. The example emphasizes development of a discharge-frequency relationship for flood damage evaluation requirements of a feasibility study. The reader should be familiar with the material in paragraph 4-6 prior to studying this example.

B2-2. General Study Background.

a. The Corps of Engineers is performing a feasibility investigation of flood loss reduction measures of the Hartgrove Drainage and Levee District. The area is primarily agricultural, but also includes the community of Wilson Grove located adjacent to the line-of-protection (see Figure B2.1). The drainage and levee district is protected from direct flooding of the Smith River to a 2-percent chance exceedance frequency event by a main levee and two tie back levees (see Figure B2.1). A single 54 inch diameter gravity outlet enables evacuation of interior floodwaters through the line-of-protection during low river stages.

b. The interior conveyance system consists of a complex network of lateral ditches connected to the main interior ditch which flows to the gravity outlet. Interior flooding along the lateral and main ditches is common when the gravity outlet is blocked by high river stages. Seepage also contributes to the interior flooding adjacent to the levee during prolonged high river stages.

B2-3. Study Strategy.

a. Reconnaissance level investigations found that significant flood damage potential exists in the Hartgrove Drainage and Levee District and that a survey study is justified to investigate alternative flood loss reduction plans. These plans include combinations of modifications to ditches, channels, and gravity outlets, and the installation of pumping facilities. Multiple discrete event analysis procedures are used to generate hydrologic data for both agricultural and urban (Wilson Grove) flood damage evaluations, optimal sizing of additional gravity outlets and pumping capacities, and selection of pump operation criteria. NOTE: Only the procedures required to develop the existing condition discharge-frequency relationship for Wilson Grove are described. Data requirements and hydrologic analysis procedures used in the plan formulation portion of the study process are described in paragraph 4-6 Multiple Discrete Event Methods, and schematically depicted in Figure 4.4.

b. The multiple discrete event analysis is performed for with and without existing and future conditions. The existing condition minimum facility

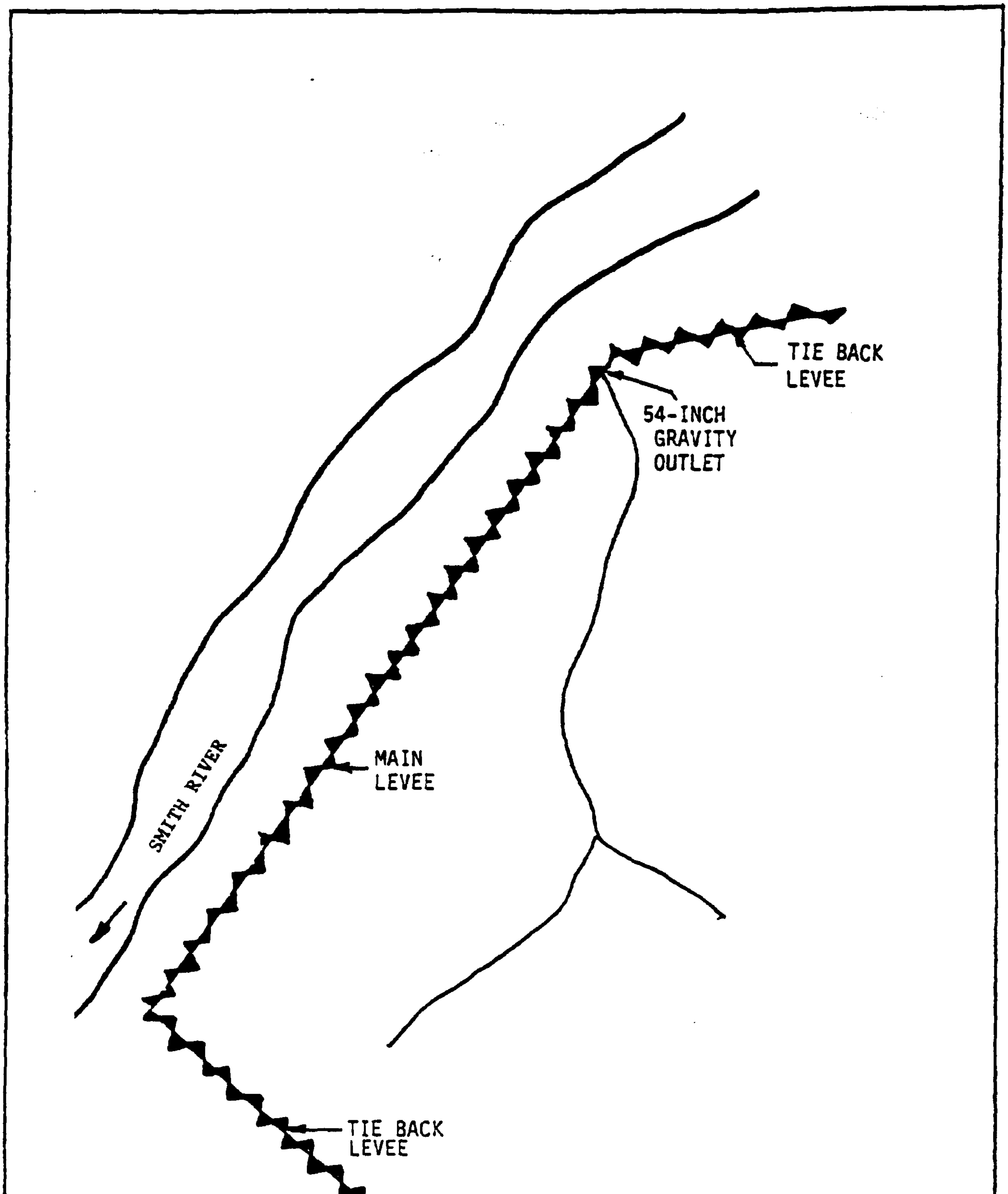


FIGURE B 2.1 Study Area Map

(reference paragraph 3-2) is assumed as the gravity outlet presently in place. The formulation strategy involves the analysis of additional gravity outlets and a range of pumping capacities. The feasibility of increased ditch conveyance is analyzed for flood damage reduction and to ensure proper volume of flood waters reach the proposed pumping plant. A series of multiple discrete events were analyzed for existing with and without project conditions.

c. The hydrologic analysis strategy for developing discharge-frequency relationships for evaluation of flood loss reduction measures for Wilson Grove is:

(1) Obtain historic rainfall and runoff (discharge and elevation) data for important events,

(2) Analyze interior flood events associated with blocked or partially blocked gravity outlet conditions,

(3) Analyze historic interior flood events associated with unblocked gravity outlet conditions,

(4) Develop annd combine the discharge-frequency relationships resulting from (2) and (3) using the joint probability theorem, and

(5) Analyze project proposal impacts on the hydrologic systems repeating steps (2) and (4).

B2-4. Hydrologic Analysis Methods.

a. General. Analysis of the interior area is performed based on data requirements for runoff response parameters, ponding area geometry, seepage, gravity outlet and pumping capacities, and exterior river stage conditions. Calculations are made for both the blocked and unblocked gravity outlet conditions. Runoff hydrographs are developed, combined, and routed throughout the interior system, and ultimately through the line-of-protection. The Wilson Grove urban damage at the gravity outlet is calculated using a discharge-frequency relationship developed from the joint probability theorem for blocked and unblocked conditions. The hydrologic analysis strategy is performed for the with and without existing and future project conditions evaluations.

b. High Exterior Stage Analysis. Historic river records of stage-discharge relationships are used to identify exterior events that might close the gravity outlet and therefore potentially produce interior flooding. The data were obtained from a nearby streamgage and transferred to the gravity outlet location by adjusting for the slope in the profile. The Smith River stage data were obtained for the period of 1934 through 1976. Thirteen events were identified as exceeding the normal gravity outlet closure stage (no interior runoff flooding). The events included all major river floods in the period-of-record. Table B2.1 lists pertinent data associated with each of the events.

Table B2.1
High Exterior Stages
Maximum Smith River Flood Events
(Period-of-Record 1934 Through 1976)

	Beginning Date of Flood Event	Duration In Days (1)	Peak W. S. Elevation at Gravity Outlet Stage (ft)	Elev. (NVGD)	Total Interior Rainfall (Inches)
1.	2 Mar 1973	131	45.6	350.4	37.82
2.	13 Jun 1969	42	39.2	344.0	3.34
3.	15 Mar 1962	62	36.2	341.0	6.43
4.	6 May 1961	27	39.5	344.3	8.62
5.	30 Mar 1960	84	38.4	343.2	7.79
6.	12 Mar 1952	81	38.3	343.1	13.86
7.	6 Jun 1951	61	41.8	346.6	8.23
8.	21 Mar 1948	38	37.8	342.6	8.63
9.	27 May 1947	108	41.8	346.6	6.86
10.	5 Mar 1945	122	38.7	343.5	20.48
11.	12 Apr 1944	99	42.8	347.6	15.26
12.	9 May 1943	76	42.4	347.2	15.67
13.	5 May 1935	79	36.4	341.2	17.62

(1) Days above gravity outlet closure stage. Closure stage corresponds to the river elevation that would result in interior damage if outlet was open and no interior runoff flooding was occurring simultaneously.

c. Interior Rainfall Analysis. Interior rainfall analysis is performed for two conditions. The first includes estimating the historic rainfall coinciding with the 13 exterior flood events. The daily totals are shown in Table B2.1. Daily totals are used due to the long duration of river flooding and lack of hourly records until 1948. The second condition is intense historic rainfall periods (over a specified duration) that might induce flooding during unblocked or low exterior river conditions. A seven day duration was adopted to insure sufficient runoff timing and volumes throughout the interior. Inspection of three nearby recording rain gages found 12 storm events of sufficient intensity to cause potential flooding and damage to the interior area. Table B2.2 lists the rainfall data associated with these 12 events. A period-of-record from 1948 to 1974 is adopted since a 6-hour time interval of analysis meets the appropriate hydrologic analysis requirements for the interior analysis during unblocked gravity outlet conditions.

Table B2.2
Low Exterior Stage

Maximum 7-Day Rainfall (1)
(Period-of Record 1948-1974)

	Date of Beginning of Storm	Total Storm Precipitation Measurements in Inches		
		(2) Raingage 1	(3) Raingage 2	(3) Raingage 3
1.	21 Jan 1949	8.51	5.29	5.12
2.	2 Oct 1949	5.62	6.05	6.13
3.	1 Jan 1950	8.01	6.47	6.89
4.	12 Aug 1950	2.61	5.84	6.60
5.	9 Aug 1952	7.64	4.89	2.18
6.	16 May 1957	5.96	6.20	10.47
7.	10 Jun 1958	4.67	10.03	5.12
8.	16 Jul 1958	.98	8.53	8.70
9.	3 Mar 1964	10.70	9.72	9.29
10.	17 Apr 1970	3.02	5.35	5.67
11.	15 Apr 1972	5.42	7.12	5.59
12.	23 Nov 1973	6.11	6.63	6.45

(1) Maximum 7-day events in May 1961 and May 1973 occurred during high Smith River conditions and are included in Table 3.
(2) Hourly precipitation recorder.
(3) Daily precipitation recorder.

d. Rainfall-Runoff Analysis:

(1) Interior Rainfall-runoff analysis is performed for each discrete event associated with blocked and unblocked gravity outlet conditions. Interior area subbasins are delineated based on hydrologic/hydraulic, flood damage, and existing and potential project locations. Runoff hydrographs are calculated from the historic rainfall patterns, adopted losses rates, unit hydrograph transforms, and base flow (including seepage conditions). The hydrographs are subsequently combined and routed throughout the interior area to the line-of-protection.

(2) A percent imperviousness adjustment is required to reflect ponding and saturated ground conditions from runoff or seepage. This adjustment is necessary for the 13 high river floods to calibrate the events and generate the appropriate volume of runoff. No adjustment is necessary to the 12 maximum 7-day storm floods associated with unblocked gravity outlet conditions.

(3) Modified Puls procedures simulated flood routings through both channel and ponding reaches. Storage-outflow data are obtained from water surface profile analyses, and area-elevation-storage data from topographic maps and surveyed sections.

e. Coincident Flood Analyses.

(1) Flood hydrographs are routed through the levee by simulating gravity outflow and/or pumping capacity associated with the exterior and interior head differential. The routings include the 13 blocked and 12 unblocked condition hydrographs. The analysis results provide peak ponding elevations adjacent to the line-of-protection.

(2) Calibration of the results is performed for the 1973 peak stage information and by data received through extensive interviews with local residents. Local residents provide data on the frequency of road overtopping, ditch and channels overflowing the banks, and drainage patterns for the flat interior area.

B2-5. Existing Without Project Conditions Analysis.

a. Existing conditions elevation-frequency relationships are developed graphically using peak elevation values determined from the interior analyses. The relationships are used to determine elevations and flood delineations associated with selected return interval events. The functions are also applied in the calculation of existing conditions expected annual damage. Table B2.3 is a tabulation of the peak interior flood elevations, for the area adjacent to the gravity outlet, for each of the 25 events analyzed.

b. Development of elevation-frequency relationships for the 12 maximum 7-day rainfall events, coinciding with low exterior (unblocked) gravity outlet conditions, is performed using Weibull's plotting positions. The peak values are arranged in descending order and plotted on probability paper using the Weibull's plotting positions. Since the data were attained from the 1948-1974 period, the denominator (N) in the Weibull plotting position equation (1/N) = 27.

c. The peak elevation-frequency relationship for the 13 high river events are similarly developed, with the exception of the plotting position for the 1973 flood event and the length of record N. The extreme flood depth and duration of this interior flood event resulted from a rare combination of long duration river flooding and corresponding extreme rainfall totals over the interior (See Table B2.1). Separate assessments resulted in an estimated .1-percent chance exceedance frequency for this event in the interior study area. Since these 13 events were the maximum for the period 1934-1975 the Weibull N value is equal to 43.

Table B2.3
Existing Conditions Interior Analysis Results
(at Gravity Outlet)
High Exterior (River) Stages

Flood Event Date	Max. Interior Water Surface Elevation (NVGD)	Weibull Plotting Position	Flood Event Date	Durations (Days) Above Gravity Outlet Closure Elevation
Mar 1973	338.2	.1*	Mar 1973	164
Mar 1945	331.3	4.5	Apr 1944	100
May 1935	331.2	6.8	Mar 1952	84
Jun 1951	330.8	9.0	May 1943	82
May 1943	330.7	11.4	Mar 1945	80
Jun 1969	330.7	13.6	Jun 1951	72
May 1947	330.4	15.9	May 1935	71
Apr 1944	330.3	18.2	May 1947	70
Mar 1960	330.3	20.5	Mar 1960	70
Mar 1952	330.2	22.7	Mar 1962	45
Mar 1948	330.0	25.0	Mar 1948	39
Mar 1961	330.0	27.3	Jun 1969	38
Mar 1962	329.6	29.5	Mar 1961	34

*Plotting position adjusted from 2.3.

Existing Conditions Interior Analysis Results
(at Gravity Outlet)
Low Exterior (River) Stages

Flood Event Date	Max. Interior Water Surface Elevation (NVGD)	Weibull Plotting Position	Flood Event Date	Durations (Days) Above Gravity Outlet Closure Elevation
May 1957	330.4	3.6	Jul 1958	29
Jul 1958	330.3	7.1	Apr 1970	28
Apr 1970	330.2	10.7	May 1957	25
Nov 1973	329.6	14.3	Apr 1972	23
Jan 1950	329.0	17.9	Nov 1973	18
Apr 1972	329.0	21.4	May 1958	18
Mar 1964	328.9	25.0	Jan 1950	18
Jan 1949	328.3	28.6	Mar 1964	16
May 1958	328.2	32.1	Jan 1949	15
Oct 1949	328.1	35.7	Aug 1952	14
Aug 1950	328.0	39.3	Aug 1950	14
Aug 1952	327.3	42.9	Oct 1949	12

d. The resulting two elevation-frequency relationships are combined by using the total probability theorem for a partial series. Table B2.4 shows the total elevation-frequency relationship for the interior ponding area adjacent to the levee at the gravity outlet.

Table B2.4
Existing Conditions Elevation-Frequency Relationship

Elevation	Probability of Interior Flooding: High River P(A)	Low River P(B)	Total Probability(1)	% Chance Exceedance Frequency
329	.600	.200	.800	80.0
330	.250	.060	.310	31.0
331	.080	.010	.090	9.0
332	.030	.001	.031	3.1
333	.016	.000	.016	1.6
334	.007	.000	.007	.7
335	.004	.000	.004	.4
336	.002	.000	.002	.2
337	.001	.000	.001	.1
338	.001	.000	.001	.1

(1) P(A) + P(B)

B2-6. Evaluation of Alternatives.

a. Feasibility assessments of flood loss reduction measures are performed for with and without existing and future project condition analyses using the basic strategy presented in paragraph 3-3. Additional gravity outlet capacity is evaluated as the initial step in the feasibility phase of the investigation. The hydrologic/hydraulic evaluations, including development of revised elevation-frequency relationships, are performed as described for existing conditions except the additional gravity outlet capacity is assumed in place. The economic evaluation shows the maximum net benefits are obtained with the addition of two 60-inch gravity outlets through the line-of-protection at the existing outlet location.

b. The existing and additional gravity outlets are adopted for the pumping capacity feasibility assessments. Evaluations of pumping plant sizes of 50-, 100-, 200-, and 500- cfs are performed for the feasibility evaluations. Maximum water surface elevations are calculated for each of the 25 historic events as described for existing conditions analyses. The economic results indicate the optimum size pumping plant to be 100 cfs. Pumping times, for operation costs analyses, are obtained by averaging the annual values for the period-of-record.

c. The feasibility assessment of other flood loss reduction measures may be performed assuming both the optimum size gravity outlet and pumping facility in place. Additional lateral channels and ditches are also required to reduce flood damage and convey flood waters to the pumping plant.

B2-7. Summary.

The multiple discrete event method provides several options of analysis. A period-of-record may be evaluated in a conventional manner using only those events that contribute to the flood problem and solution. This may significantly reduce the data processing and calibration tasks. The analysis of discrete events also makes available other single event analytical tools which typically enable evaluation of more complex hydrologic systems than those designed for period-of-record. Flood damage evaluations may be performed by event (most common for agricultural areas) or by development of exceedance frequency relationships as demonstrated in this example.

EXHIBIT B3

COINCIDENT FREQUENCY

B3-1. Purpose. This exhibit describes a case example of the coincident frequency method of performing hydrologic studies for a leveed interior area. The example emphasizes calculation concepts of the method in a feasibility study setting. Two flood seasons are analyzed to demonstrate methods of combining seasonal frequency relationships using the total probability theorem. Calculation examples are limited to existing without project conditions analysis. The reader should be familiar with the material in paragraph 4-8, Coincident Frequency Methods, prior to studying this example.

B3-2. General Study Background.

a. The Corps of Engineers is performing a planning feasibility study of the leveed interior area. The study area is the flood plain portion of an urban area along the Smith River which encompasses 5.2 square miles and is protected from direct river flooding to the Standard Project flood protection level. The study area is heavily developed with both manufacturing and commercial businesses (see Figure B3.1).

b. The interior area has a maximum water course length of 3.6 miles with an estimated imperviousness factor of 35 percent. The interior topography slopes gently to the river. An existing 54 inch circular gravity outlet passes interior flood waters through the line-of-protection for positive head differentials with the Smith River.

c. The Smith River has a drainage area of approximately 20,000 square miles above the study area. Daily stage records obtained from a nearby river gage data are available from 1929 to 1976. The mean daily discharge for the period is estimated to be 18,000 c.f.s.

d. Interior flooding typically occurs from moderate to heavy rainfall when the gravity outlet is blocked from high river stages. During low river stages the gravity outlet provides interior protection up to a one percent chance exceedance frequency event. Existing interior ponding is primarily limited to streets, parking lots, and a small amount of vacant land. Additional ponding locations are not economically and socially feasible.

B3-3. Study Strategy.

a. General Procedure. (1) A reconnaissance investigation has found that significant damage potential exists and that a feasibility study is justified to investigate alternative flood loss reduction plans. These plans include combinations of structural (gravity outlets, pumping facilities, and ditches) and nonstructural (flood proofing, relocation, regulations and flood warning-emergency preparedness) measures.

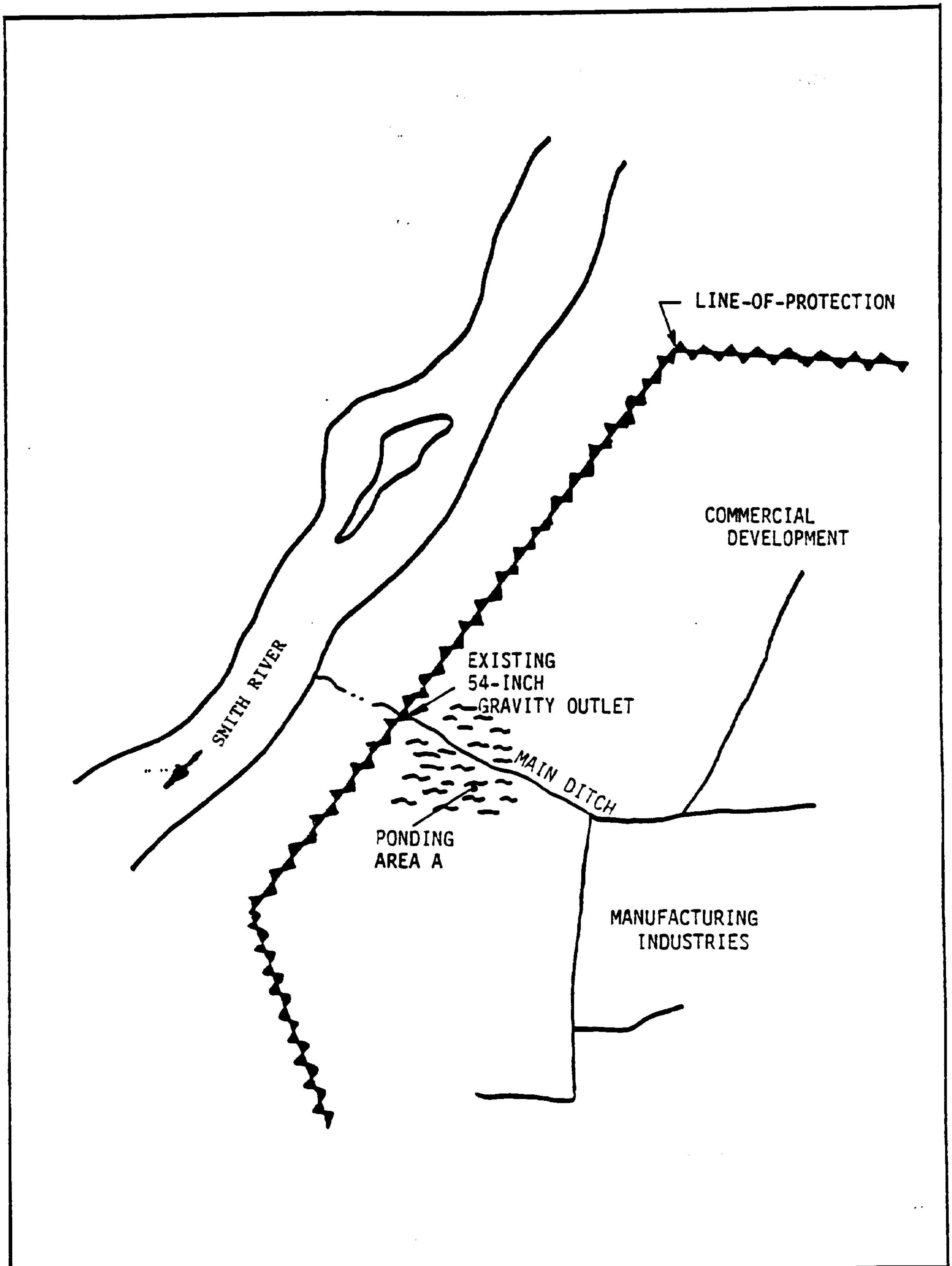


FIGURE B 3.1 Study Area Map

(2) Coincident frequency techniques are used to generate hydrologic data for flood damage evaluations, measure performance appraisals, determine the optimal sizing of plan components, and define the operation criteria of the adopted plan. Assessment of interior and exterior flooding shows a high degree of coincidence (high river stages coinciding with interior rainfall-runoff) between the river and interior flooding. However, the dependence of the events is low due to the relative size of the river drainage area with that of the interior study area (reference Table 4.1). The urban damage potential of the study area is such that detailed duration and seasonal analyses is not needed. The low-dependence of the interior and exterior events, urban flood damage potential, and simplistic interior hydrologic system make the coincident analysis procedures appropriate for this study.

(3) Adopted procedures for performing existing condition analyses are: (a) development of exterior stage data, (b) rainfall-runoff analyses of the interior areas, and (c) development of coincident stage-frequency functions. The plan formulation and evaluation strategy involves repeating (a) through (b) for each alternative analyzed. Subsequent paragraphs detail the hydrologic analysis procedures used to develop existing conditions discharge-frequency relationships. Two flood seasons are evaluated to demonstrate the process only, and are not normally required for urban damage analyses. Multiple flood season analysis may be required when flood damage is seasonally based, such as agricultural crop damage.

b. Exterior Stage-Duration Relationships. (1) Observed river daily flow estimates are used to determine the flow- and stage-duration relationships at the gage location. The data are adjusted to the nearby gravity outlet site accounting for differences in slope and rating curves between the locations. Inspection of river data indicates two distinct hydrologic seasons: (a) a flood season from April through June; and (b) a nonflood season from July through March. Figures B3.2, B3.3, and B3.4 show the annual flood season, and nonflood season stage-duration relationships for the river.

(2) Index Stage Values. Exterior index values (river elevations), required for the coincident frequency analysis, are obtained from the flow duration curve for the river. The index values represent the midpoint of the stage intervals selected for the analysis. Figures B3.3 and B3.4 show the flood season probabilities (actually percent of time exceeded) values obtained from the stage-duration relationships for each river stage used in the analysis. (NOTE: Interior analyses involving additional Smith River stage values would result in better definition of the probability intervals and more accurate results.) The nonflood season probability intervals were determined in a similar manner but are not shown (reference Figure 4.7). Table B3.1 shows the index location and associated probability of flooding for the river.

c. Interior Rainfall-Runoff Analysis. (1) The interior analysis requires development of a series of hypothetical frequency hydrographs associated with each of the index exterior stage conditions. Rainfall-runoff parameters are defined for each interior subbasin. The frequency hydrographs are routed throughout the interior system to the gravity outlet location.

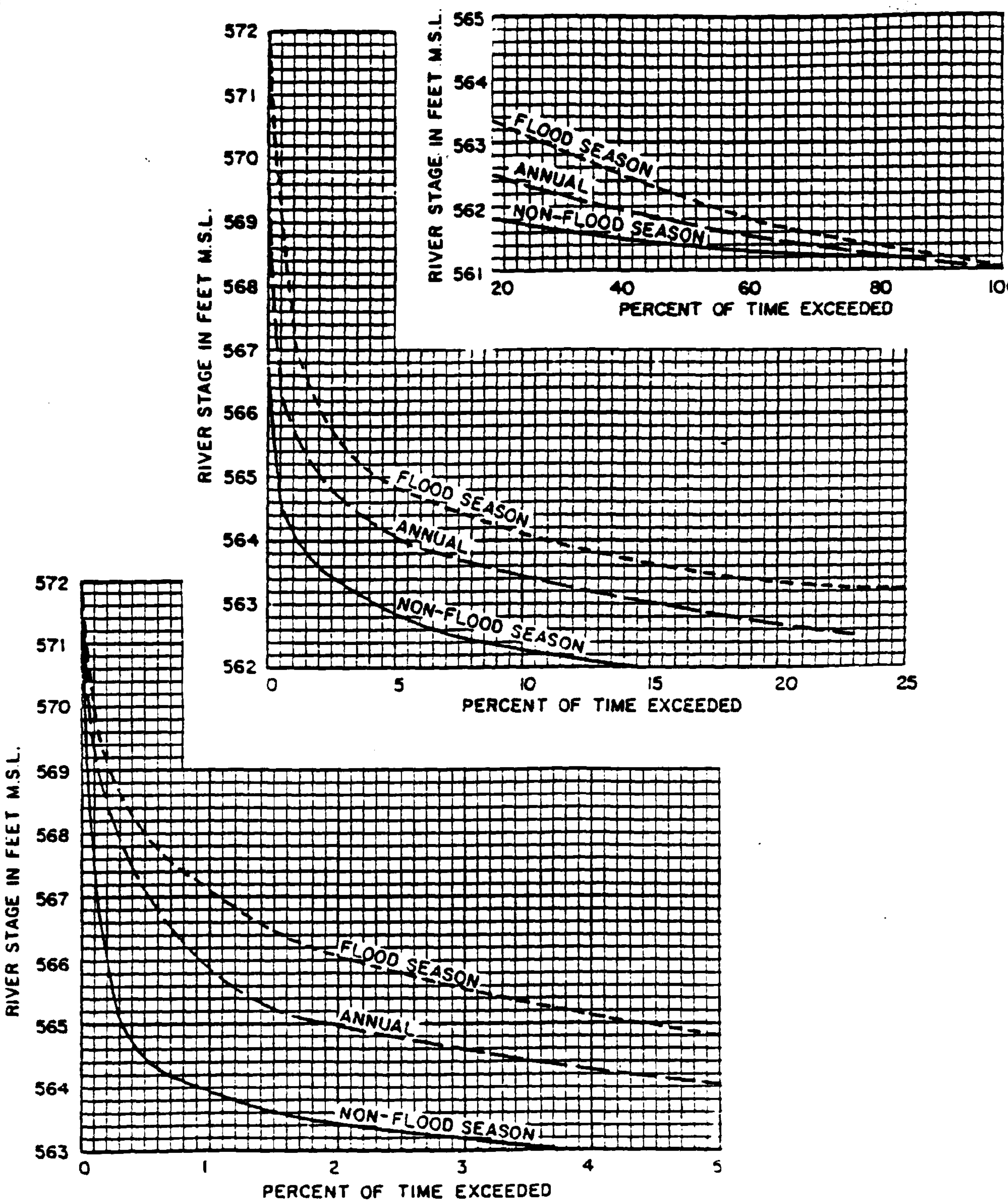


FIGURE B3.2 Seasonal Stage-Duration Relationships

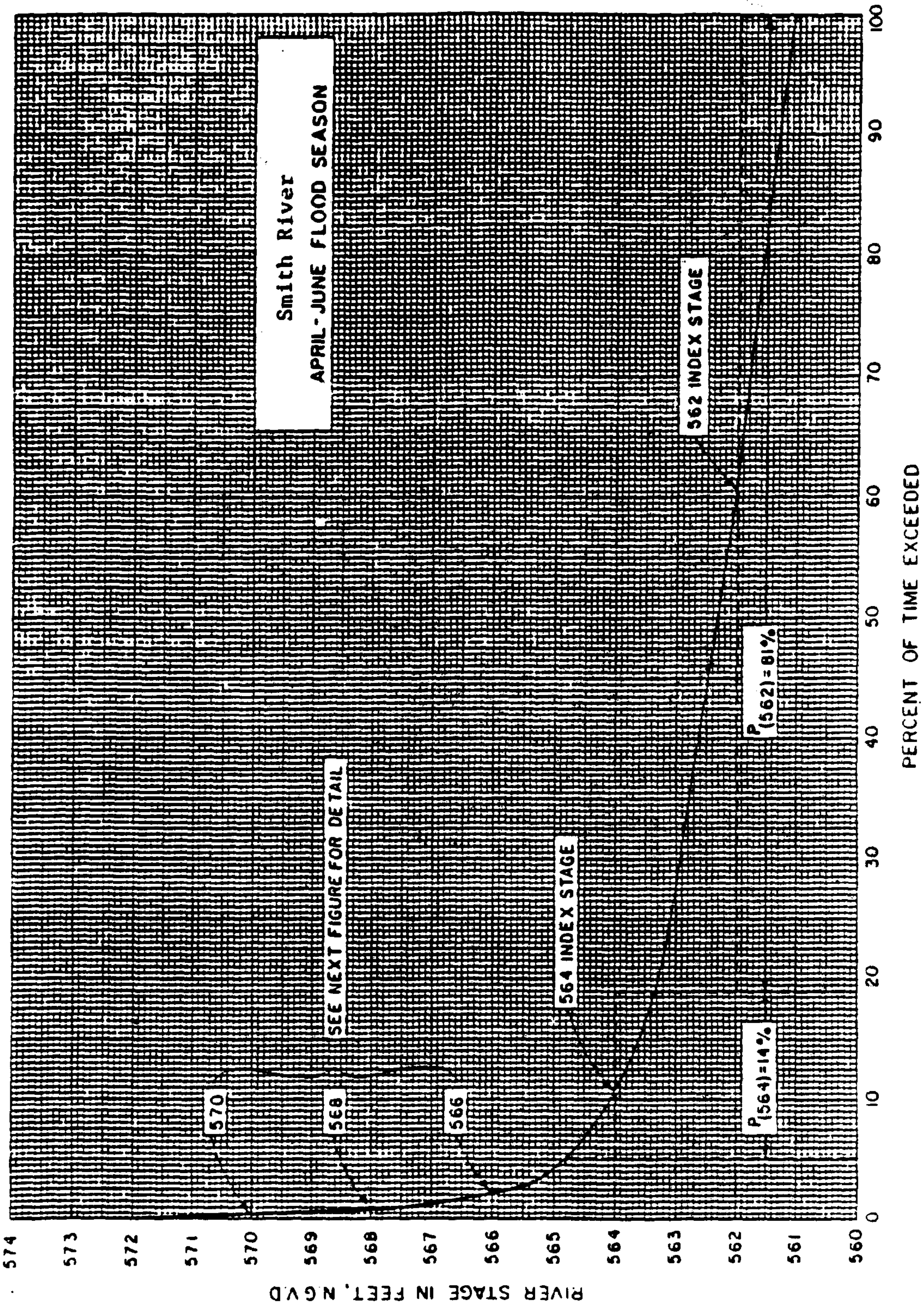


FIGURE B3.3 Flood Season Stage-Duration Relationships

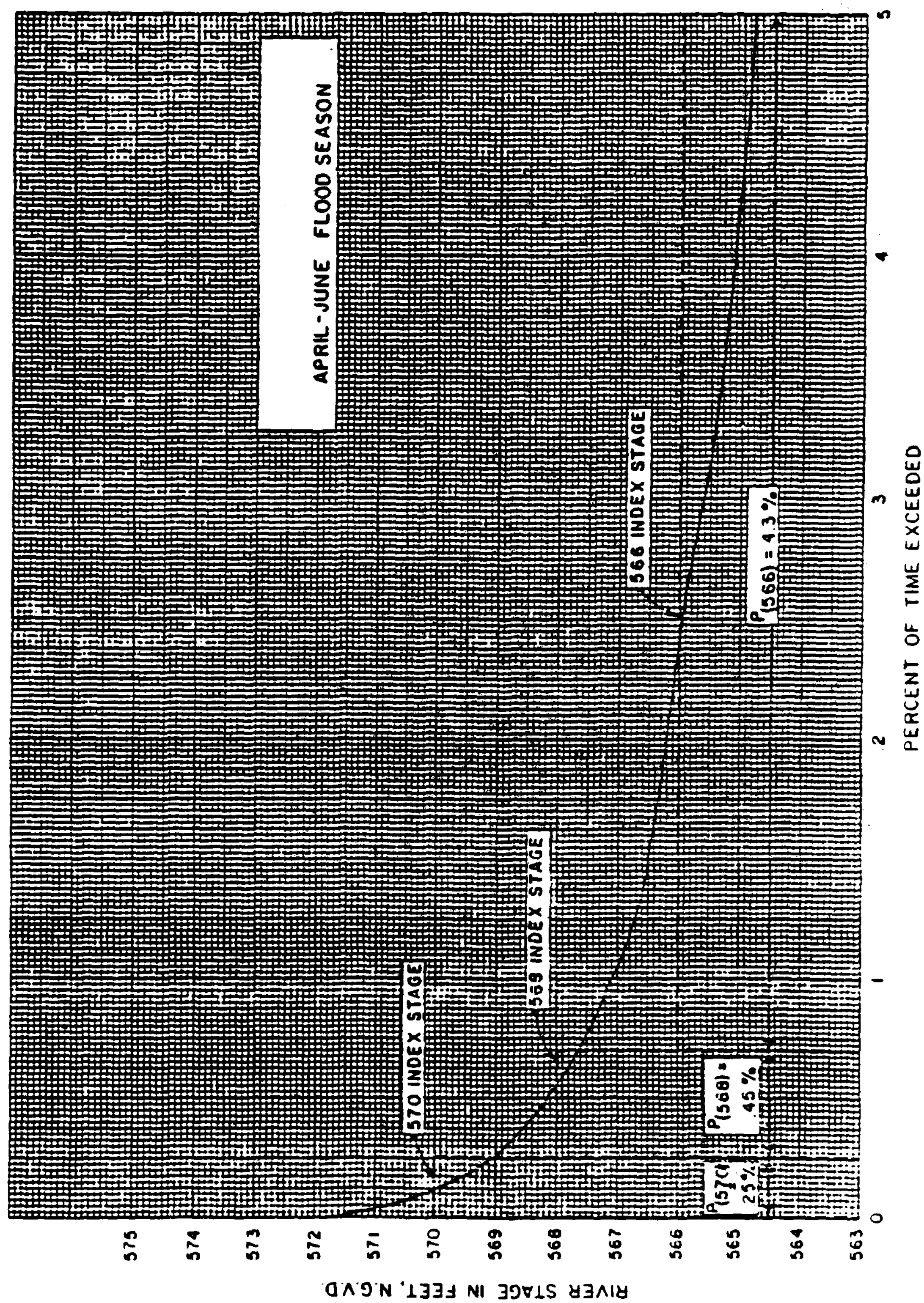


FIGURE B3.4 Flood Season Stage-Duration Relationships

(2) Rainfall Data. Hypothetical precipitation-frequency-duration annual rainfall data are used to generate interior subbasin runoff hydrographs. One hour to 10 days precipitation data are obtained from National Weather Service (NOAA) Technical publications. A 10-day rainfall duration is used to generate runoff hydrographs of appropriate volume associated with the potential long periods of high river conditions.

(3) Runoff Analysis. Rainfall excess patterns for each subbasin are calculated from hypothetical frequency storm data and loss rate parameters. The subbasin rainfall excess is transformed to runoff hydrographs at the outlet of the subbasin using a unit hydrograph. A set of interior frequency runoff events (50-, 10-, 5-, 2-, 1-, and .2 percent chance exceedance frequency assignments) are determined for each index river stage. The analyses are performed by season for existing and each modified condition. Approximated base flow and seepage inflow values are added to each event based on observed interior flow data and head differences with the river index stages, respectively.

Table B3.1
Smith River Index Stage Data

Stage Interval (Feet)	Index Stage (Feet NVGD)	Proportion of Time Stage Exceeded: Flood Season (April-June)	Proportion of Time Stage Exceeded: Nonflood Season (July-March)
558-562	560 (B_1)	.8100	.9750
562-565	564 (B_2)	.1400	.0210
565-567	566 (B_3)	.0430	.0028
567-569	568 (B_4)	.0045	.0012
569-571	570 (B_5)	.0025	.0000
		1.0000	1.0000

(4) Flood Routings. Modified Puls routing procedures are used to approximate the flood hydrograph attenuation that occurs through the conveyance and natural storage systems of the interior area. Gravity outflow routings are performed for positive head differentials between the interior and exterior stage levels. The resulting stage-frequency results are subsequently calibrated to observe event flood levels in the interior area.

(d) Coincident Frequency Analysis.

(1) Coincident frequency analysis is performed to determine peak interior water surface elevations associated with the river index stages. Flood probability values for Pond A (P(A)), given the probability (P(B)) of the river at a specified stage, are then calculated. The probability value P(A) is termed the conditional probability of the interior Pond A.

(2) The conditional probability values are subsequently used to develop a weighted stage-frequency function for Pond A for each season. Tables B3.2 and B3.3 show the coincident probability values, weighted probability computation procedures and values, and total stage-probability (exceedance frequency) relationships of Pond A for the flood and nonflood seasons, respectively.

(3) The composite stage-frequency relationship for both the flood and nonflood season is obtained by combining the two seasonal functions using the total probability theorem. The total probability relationship P_T for this example, a partial series, is obtained by the equation $P_T = P(1) + P(2)$, where P(1) equals the flood season stage probability and P(2) the nonflood season probability associated with the same stage. For an annual series analysis the total probability theorem equation is $P_T = P(1) + P(2) - P(1) \times P(2)$. The term $P(1) \times P(2)$ represents the joint probability of occurrences of the events. The numeric values, example computations, and the stage-frequency relationship are depicted in Table B3.4.

(4) Similar computation procedures are required to develop coincident stage-frequency functions for existing and future with and without conditions (not presented herein).

B3-4. Summary and Discussion.

a. The coincident analysis procedure described is directly applicable to areas where exterior and interior flood events are independent. It is often useful to analyze the two extreme conditions which bracket the results prior to initiating a complete coincident frequency analysis. These conditions are (1) completely blocked gravity outlets; and (2) completely open gravity outlets. The results of these basic analyses will provide insights into whether additional studies are required, the level of detail necessary for additional studies, and identify potential alternatives to investigate.

b. The frequency relationships defined by probabilities P(1) and P(2) may be either an annual or partial series. However, both frequency relationships must be the same type for the analyses.

Table B3.2

Development of Maximum Interior Water Surface Elevation - Frequency Relationships for Existing Without Project Conditions (Flood Season April - June)

Interior Pond Water Surface Elevation (A) (Feet NVGD)	Probability of Exceeding Pond "A" Given River Stage "B_i" (Conditional Probability $P_1(A/B_i)$)*					Weighted Probability for Interior POND Elevations $P_1(A)$
	River Stage $B_1 = 560$ Stage Prob. $P(B_1) = .8100$	River Stage $B_2 = 564$ Stage Prob. $P(B_2) = .1400$	River Stage $B_3 = 566$ Stage Prob. $P(B_3) = .0430$	River Stage $B_4 = 568$ Stage Prob. $P(B_4) = .0045$	River Stage $B_5 = 570$ Stage Prob. $P(B_5) = .0025$	
564	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
565	.5000	1.0000	1.0000	1.0000	1.0000	.5950
566	.1000	.4800	1.0000	1.0000	1.0000	.1982
567	.0100	.0700	1.0000	1.0000	1.0000	.0679
568	.0008	.0032	.0300	1.0000	1.0000	.0093
569	.0000	.0002	.0006	.0380	.3100	.0010
570	.0000	.0000	.0000	.0020	.2500	.0001
571	.0000	.0000	.0000	.0000	.0000	.0000

*Interior pond probability (exceedance frequency) values associated with the Smith River stages values are determined from hypothetical frequency flood event analyses of the interior for each river stage. Flood waters are routed through the line-of-protection (gravity outlet) during positive head.

NOTE: Example of weighted probability computations (*Reference Figure 4.7, page 37*), using interior elevation of 568, where:

$$P_1(A) = P_1(A/B_1) \times P(B_1) + P_1(A/B_2) \times P(B_2) + P_1(A/B_3) \times P(B_3) + P_1(A/B_4) \times P(B_4) + P_1(A/B_5) \times P(B_5)$$

$$= .0008(.8100) + .0032(.1400) + .0300(.0430) + 1.0000(.0045) + 1.0000(.0025)$$

$$= .0093$$

Table B3.3

Development of Maximum Interior Water Surface
Elevation - Frequency Relationships for Existing Without Project Conditions
(Nonflood Season July - March)

Interior Pond Water Surface Stage Prob. (Feet NVGD)	Probability of Exceeding Pond "A" Given River Stage "B_i" (Conditional Probability $P_1(A/B_i)$)*				Weighted Probability For Interior Pond Elevations $P_2(A)$
	River Stage $B_1 = 562$ Stage Prob. $P(B_1) = .9750$	River Stage $B_2 = 564$ Stage Prob. $P(B_2) = .0210$	River Stage $B_3 = 566$ Stage Prob. $P(B_3) = .0028$	River Stage $B_4 = 568$ Stage Prob. $(B_4) = .0012$	
564	1.0000	1.0000	1.0000	1.0000	1.0000
565	.3700	1.0000	1.0000	1.0000	.3858
566	.1200	.5400	1.0000	1.0000	.1302
567	.0150	.1700	.7000	1.0000	.0214
568	.0004	.0140	.1100	1.0000	.0022
569	.0000	.0008	.0045	.1500	.0002
570	.0000	.0002	.0004	.0060	.0000
571	.0000	.0000	.0002	.0009	.0000

*Interior pond probability (exceedance frequency) values associated with individual Smith River stage values are determined from hypothetical frequency flood event analyses of the interior for each river stage. Flood waters are routed through the line-of-protection (gravity outlet) during positive head conditions.

NOTE: Example of weighted probability computations (Reference Figure 4.7, page 37), using interior elevation of 568, where:

$$P_2(A) = P_2(A/B_1) \times P(B_1) + P_2(A/B_2) \times P(B_2) + P_2(A/B_3) \times P(B_3) + P_2(A/B_4) \times P(B_4)$$

$$= .0004(.9750) + .0140(.0003) + .1100(.0003) + 1.0000(.0012)$$

$$= .0022$$

TABLE B3.4
Existing Without Project Conditions Stage-Probability (Exceedance Frequency) for Interior Pond Elevation*

Interior Pond Elevation (A) (Feet NVGD)	Flood Season Interior Pond Elevation Prob $P_1(A)$	Nonflood Season Interior Pond Elevation Prob. $P_2(A)$	Total Probability Interior Pond Elevation Prob. $P(A)$	Percent Chance Exceedance Frequency
564	1.0000	1.0000	1.0000	100.00
565	.5950	.3858	.9808	98.10
566	.1982	.1302	.3284	32.80
567	.0679	.0214	.0893	9.00
568	.0093	.0022	.0115	1.00
569	.0010	.0002	.0012	.10
570	.0001	.0000	.0001	.01

* Example computation of total probability theorem for Pond A using water surface elevation 568, where:

$$P(A) = P_1(A) + P_2(A)$$

$$= .0093 + .0022$$

$$= .0115$$